

# Arctic Sea Ice Export through Fram Strait and Atmospheric Planetary Waves

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## Abstract

A link is found between the variability of Arctic sea ice export through Fram Strait and the phase of the longest atmospheric planetary wave (zonal wave 1) in SLP for the period 1958-1997. Previous studies have identified a link between Fram Strait ice export and the North Atlantic Oscillation (NAO), but this link has been described as unstable because of a lack of consistency over time scales longer than the last two decades. Inconsistent and low correlations are also found between Fram Strait ice export and the Arctic Oscillation (AO) index. This paper shows that the phase of zonal wave 1 explains 60%-70% of the simulated Fram Strait ice export variance over the 40-year period 1958-1997. Unlike the NAO and AO links, these high variances are consistent for both the first and second halves of the 40-year period. This consistency is attributed to the sensitivity of the wave 1 phase at high latitudes to the presence of secondary low pressure systems in the Barents Sea that serve to drive sea ice southward through Fram Strait. These results provide further evidence that the phase of zonal wave 1 in SLP at high latitudes drives regional as well as hemispheric low frequency Arctic Ocean and sea ice variability.

## **POPULAR SUMMARY**

### **Arctic Sea Ice Export through Fram Strait and Atmospheric Planetary Waves**

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This paper describes a link between Arctic sea ice export through Fram Strait and variations in the phase of the longest atmospheric planetary-scale wave (zonal wave 1) in sea level pressure (SLP). Arctic sea ice export through Fram Strait is an important climate parameter that serves to modulate the North Atlantic thermohaline circulation. Previous studies have found a link between the ice export through Fram Strait and the North Atlantic Oscillation (NAO), but this link has been described as unstable because of a lack of consistency over time scales longer than the last two decades. Inconsistent and low correlations are also found between Fram Strait ice export and the Arctic Oscillation (AO) index. This paper shows that the phase of zonal wave 1 explains 60%-70% of the simulated Fram Strait ice export variance over the 40-year period 1958-1997. Unlike the NAO and AO links, these high variances are consistent for both the first and second halves of the 40-year period. This consistency is attributed to the sensitivity of the wave 1 phase at high latitudes to the presence of secondary low pressure systems in the Barents Sea that serve to drive sea ice southward through Fram Strait. These results provide further evidence that the phase of zonal wave 1 in SLP at high latitudes drives regional as well as hemispheric low frequency Arctic Ocean and sea ice variability.

## **SIGNIFICANT FINDINGS WITH RELATION TO MTPE**

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The significance of this paper is that it provides a link between Arctic sea ice export through Fram Strait and variations in the phase of the longest atmospheric planetary-scale wave (zonal wave1) in sea level pressure (SLP). Arctic sea ice export through Fram Strait is an important climate parameter that serves to modulate the North Atlantic thermohaline circulation. Previous studies have found a link between ice export through Fram Strait and the North Atlantic Oscillation (NAO), but this link has been described as unstable because of a lack of consistency over time scales longer than the last two decades. Inconsistent and low correlations are also found between Fram Strait ice export and the Arctic Oscillation (AO) index. This paper shows that the phase of zonal wave 1 explains 60%-70% of the simulated Fram Strait ice export variance over the 40-year period 1958-1997. Unlike the NAO and AO links, these high variances are consistent for both the first and second halves of the 40-year period. This consistency is attributed to the sensitivity of the wave 1 phase at high latitudes to the presence of secondary low pressure systems in the Barents Sea that serve to drive sea ice southward through Fram Strait. These results provide further evidence that the phase of zonal wave 1 in SLP at high latitudes drives regional as well as hemispheric low frequency Arctic Ocean and sea ice variability. This research supports NASA's Earth Science Enterprise science goal of observing and understanding how the Earth climate system is changing.

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### **Abstract**

A link is found between the variability of Arctic sea ice export through Fram Strait and the phase of the longest atmospheric planetary wave (zonal wave 1) in SLP for the period 1958-1997. Previous studies have identified a link between Fram Strait ice export and the North Atlantic Oscillation (NAO), but this link has been described as unstable because of a lack of consistency over time scales longer than the last two decades. Inconsistent and low correlations are also found between Fram Strait ice export and the Arctic Oscillation (AO) index. This paper shows that the phase of zonal wave 1 explains 60%-70% of the simulated Fram Strait ice export variance over the 40-year period 1958-1997. Unlike the NAO and AO links, these high variances are consistent for both the first and second halves of the 40-year period. This consistency is attributed to the sensitivity of the wave 1 phase at high latitudes to the presence of secondary low pressure systems in the Barents Sea that serve to drive sea ice southward through Fram Strait. These results provide further evidence that the phase of zonal wave 1 in SLP at high latitudes drives regional as well as hemispheric low frequency Arctic Ocean and sea ice variability.

### **Introduction**

Arctic sea ice export through Fram Strait is an important climate parameter that serves to modulate the North Atlantic thermohaline circulation (Mauritzen and Häkkinen, 1997). The

link between the ice export through Fram Strait and the North Atlantic Oscillation (NAO) has received considerable attention recently (e.g., Kwok and Rothrock, 1999; Dickson et al., 2000; Hilmer and Jung, 2000; Jung and Hilmer, 2001; Vinje, 2001), but the mechanism by which the atmosphere drives the ice export on time scales longer than the last two decades remains in question.

Over a 5-year period, Kwok and Rothrock (1999) found a correlation of 0.56 between the volume flux of ice through Fram Strait and the winter NAO, while for the 20-year period 1976-1995, Dickson et al. (2000) found that the NAO explains about 60% of the variance in the Fram Strait ice flux, but they suspect that the high correlation breaks down for longer periods. On the other hand, Hilmer and Jung (2000) discovered no significant correlation between Arctic sea ice export and the NAO from 1958 to 1977, but for the period 1978-1997 the correlation increased to 0.7. Most recently, Vinje (2001) obtained a correlation of only 0.1 between the Fram Strait ice export and the NAO index from an analysis of a 50-year time series (1950-2000) of parameterized monthly ice volume flux through Fram Strait. Hilmer and Jung (2000) found the same low correlation for the 40-year period 1958-1997. Over the period 1976-1996, Dickson et al. (2000) obtain a correlation of 0.77 from parameterized ice volume flux. Vinje (2001) found a negative correlation of  $-0.32$  for the period 1962-1978 and also discovered that only for certain periods is there a significant correlation between the NAO and the Arctic ice flux. Vinje (2001) sums up the situation by stating that recent observational and modeling studies provide evidence of an unstable link between the NAO and ice export through Fram Strait.

In this study, comparisons are made between the January Fram Strait ice export and corresponding values for (a) the NAO index, (b) the Arctic Oscillation (AO) index, and (c) the phase of the longest planetary-scale SLP wave, zonal wave 1, for the period 1958-1997. Based on the results of these comparisons, we conclude that fluctuations in the phase of zonal wave 1

provide a reasonable mechanism by which most of the Fram Strait ice flux variance can be explained over the 40-year period.

## Results

Simulated ice volume transport through Fram Strait was obtained for the 40-year period 1958-1997 from two dynamic-thermodynamic ice models. The reason for using simulations from two different ice models is to show that the results presented are not model specific. The first model is a coupled ice-ocean model forced by monthly surface wind and air temperature data derived from the NCEP/NCAR reanalysis project and is described by Häkkinen and Geiger (2000). The second model is forced by daily surface wind and air temperature data also derived from the NCEP/NCAR reanalysis project (Hilmer, 2001). Trenberth's Northern Hemisphere monthly sea level pressure (SLP) grids obtained from NCAR were analyzed for the same 40-year period to obtain phase and amplitude information of the longest planetary-scale waves for the latitude band  $70^{\circ}$  N to  $80^{\circ}$  N following the procedure described by Cavalieri and Häkkinen (2001). The monthly NAO indices were obtained from Jim Hurrell's web site at NCAR and the monthly AO indices were obtained from the atmospheric science web site at Colorado State University. Comparisons are made for the month of January when the wintertime atmospheric circulation is well developed.

Time series of the January Fram Strait simulated ice export from both models versus the January NAO index, the January AO index, and the January phase of zonal wave 1 for the  $70^{\circ}$  -  $80^{\circ}$  N latitude band are shown in Figure 1. Examination of this figure shows that both the NAO and AO indices exhibit a negative correlation from 1958 until the mid 1970's when the correlation then becomes positive for the remainder of the period. In contrast, the association with the phase of wave 1 is positive for the entire 40-year period except in the mid 1960's when there was a rapid eastward shift in phase preceding the reduction in amplitude of the dominant

wave 1 high latitude circulation pattern (Cavalieri and Häkkinen, 2001). Examination of Figure 1 also shows the high correlation between the ice export simulations from the two models. For this reason, the January Fram Strait ice export data shown in the scatter plots of Figure 2 are from the Häkkinen and Geiger (2000) model only. Figure 2 shows the Fram Strait ice export for the years 1958-1997 versus (a) the NAO index, (b) the AO index, (c) wave 1 phase, and (d) wave 1 phase without the inclusion of 1966 and 1967. The wave 1 phase for these two years appear to be anomalous and as mentioned previously preceded the breakdown of the high latitude wave 1 atmospheric circulation in the mid 1960's (Cavalieri and Häkkinen, 2001). The ice flux variance explained by the NAO index is 0.00 over this period, a result consistent with Hilmer and Jung (2000). Similarly, the variance explained by the AO index is also insignificant, but the variance explained by the wave 1 phase at a latitude of 70-80 N is 37% and increases to 71% when the two anomalous years 1966 and 1967 are removed.

The 40-year period 1958-1997 is next divided into two halves to examine the consistency of the relatively high correlation between the Fram Strait ice export and the phase of wave 1. The results are shown in Figure 3. The correlations for both the NAO and AO indices reverse sign for the two periods going from negative to positive, while the correlation involving the wave 1 phase is consistently positive. Table 1 provides a summary of the variances explained as well as the correlations for each index and the wave 1 phase for the entire 40-year period and for the first and second 20-year periods. The results for both sets of simulated ice flux are included. The results show generally small variances and correlations for the NAO and AO indices for the individual periods and an even smaller overall correlation resulting from the change in sign between the two halves. The negative correlation between the simulated Fram Strait ice fluxes and the NAO index for the first half is  $-0.32$  and  $-0.31$  for the Häkkinen and Hilmer simulations respectively, in agreement with the negative correlation ( $-0.32$ ) obtained by Vinje (2001) for the

period 1962-1978. In contrast, the correlations obtained using the phase of wave 1 are consistently about 0.8 for both simulated ice flux data sets for all three time periods.

**Table 1.** January Fram Strait Ice Export variance explained by the January NAO index, the January AO index, and the January wave 1 phase both for the entire 40-year period and for the first and second 20-year periods from a linear regression analysis. The phase values for years 1966 and 1967 were not included. Corresponding correlations are within parentheses. Results obtained using both the Häkkinen and Hilmer simulations are shown for each case.

Period	NAO		AO		Wave 1 Phase	
	Häkkinen	Hilmer	Häkkinen	Hilmer	Häkkinen	Hilmer
1958-1979	0.10 (-0.32)	0.10 (-0.31)	0.01 (-0.12)	0.01 (-0.12)	0.72 (+0.85)	0.62 (+0.79)
1980-1997	0.02 (+0.15)	0.03 (+0.17)	0.09 (+0.30)	0.11 (+0.34)	0.72 (+0.85)	0.60 (+0.77)
1958-1997	0.0 (-0.04)	0.00 (0.00)	0.01 (+0.12)	0.03 (+0.18)	0.71 (+0.84)	0.59 (+0.77)

## Discussion

A comparison of a 40-year record of simulated Fram Strait ice export with both the NAO and AO indices reveals poor correlations both for the overall period as well as for the first (1958-1979) and second (1980-1997) 20-year records separately. The results for the NAO index agree with previously reported correlations (e.g., Vinje, 2001) and reasons for the poor correlations have been discussed previously by Häkkinen and Geiger (2000), Jung and Hilmer (2001), and Vinje (2001). Mean SLP maps for the first and second 20-year periods are shown in Figures 4a and 4b, respectively. The mean SLP pattern for the second period (Figure 4b) is indicative of a high NAO pattern. This and the presence of a secondary low in the Norwegian Sea (the mean



SLP in the region was 8 mb lower on average than during the first 20-year period) explain the positive correlations for the second 20-year period. This result is consistent with the findings of Jung and Hilmer (2001). They suggest that the positive correlations reported result from an eastward shift in the NAO's center of interannual variability during this period. They also suggest that this NAO pattern and the high correlation for the 20-year period are unusual at least in the context of natural climate variability.

The phase of wave 1 explains 60%-70% (correlation is about 0.8) of the simulated Fram Strait ice export variance. The variances and positive correlations are consistent for the first and second 20-year periods examined as well as for the entire 40-year period. This consistency is attributed to the variation of the wave 1 phase between two extreme modes (Cavalieri and Häkkinen, 2001). The extreme eastward mode is shown in Figure 4c and is characterized by the extension of the Icelandic Low into the Barents Sea, whereas the extreme westward mode shown in Figure 4d is characterized by a deeper Icelandic Low that does not extend into the Barents Sea. The latter mode is somewhat similar to the positive NAO pattern. As discussed by Cavalieri and Häkkinen (2001) and also noted by others (Häkkinen, 1993; Hilmer et al., 1998), the extension of low pressure into the Barents Sea provides the forcing for ice export through Fram Strait. The results presented show that the phase of zonal wave 1 at high latitudes is a highly consistent measure of this extension of low pressure into the Barents Sea and as such provides a useful index for monitoring ice export through Fram Strait.

### **Acknowledgments**

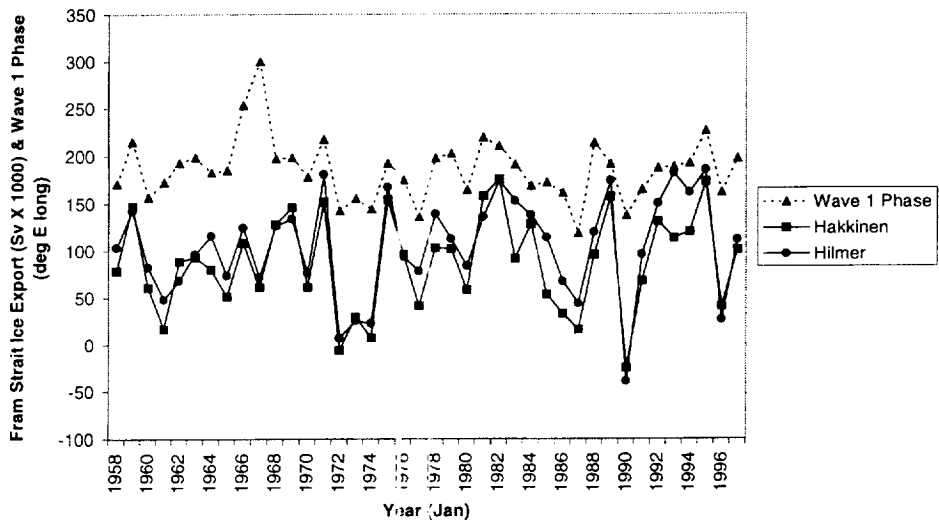
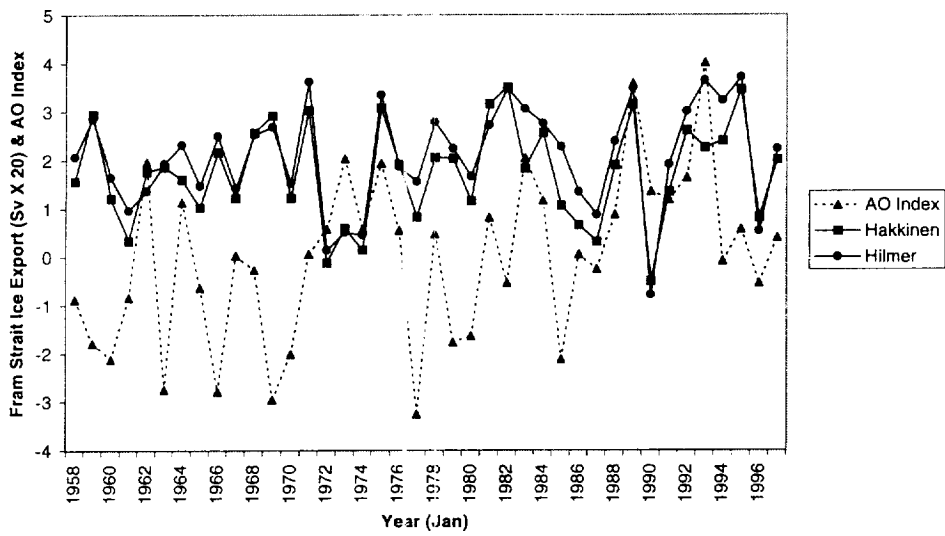
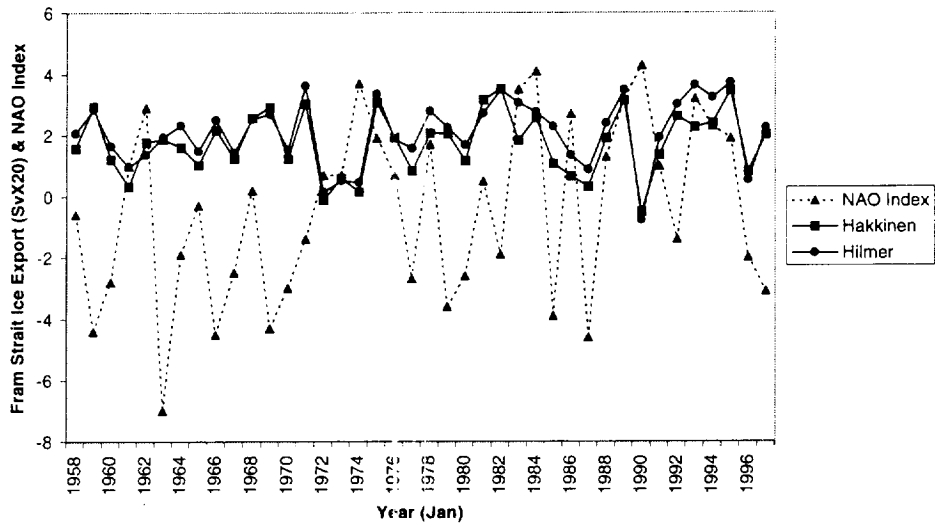
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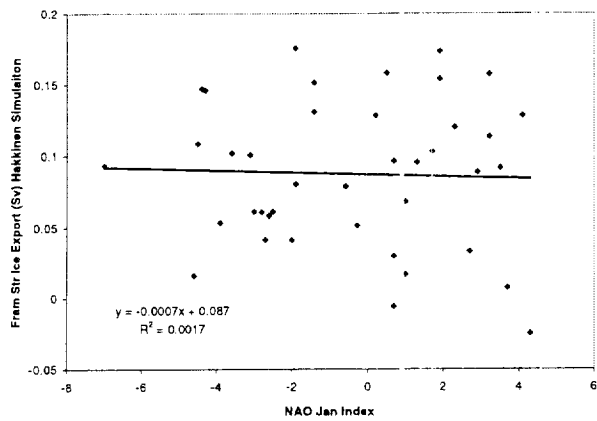
## References

- Cavalieri, D. J. and S. Häkkinen, Arctic climate and atmospheric planetary waves, *Geophys. Res. Lett.*, 28, 791-794, 2001.
- Dickson, R. R., T. J. Osborn, J. W. Hurrell, J. Meincke, J. Blindheim, B. Adlandsvik, T. Vinje, G. Alekseev, and W. Maslowski, The Arctic Ocean response to the North Atlantic Oscillation, *J. Climate*, 13, 2671-2696, 2000.
- Häkkinen, S., An Arctic Source for the Great Salinity Anomaly: A Simulation of the Arctic Ice-Ocean System for 1955-1975, *J. Geophys. Res.*, 98, 16,397-16,410, 1993.
- Häkkinen, S. and C. A. Geiger, Simulated low-frequency modes of circulation in the Arctic Ocean, *J. Geophys. Res.*, 105, 6549-6564, 2000.
- Hilmer, M., A Model Study of Arctic sea Ice Variability, Thesis, Institut für Meereskunde of the Christian-Albrechts-Universität Kiel, Germany, 2001.
- Hilmer, M. and T. Jung, Evidence for a recent change in the link between the North Atlantic Oscillation and Arctic sea ice export, *Geophys. Res. Lett.*, 27, 989-992, 2000.
- Hilmer, M., M. Harder, and P. Lemke, Sea ice transport: A highly variable link between Arctic and North Atlantic, *Geophys. Res. Lett.*, 25, 3359-3362, 1998.
- Jung, T. and M. Hilmer, The link between the North Atlantic Oscillation and Arctic sea ice export through Fram Strait, *J. Climate*, 14, 3932-3943, 2001.
- Kwok, R. and Rothrock, D. A., Variability of Fram Strait ice flux and North Atlantic Oscillation, *J. Geophys. Res.*, 104, 5177-5189, 1999.
- Mauritzen C., and S. Häkkinen, Sensitivity of thermohaline circulation to sea-ice forcing in an arctic-North Atlantic model, *J. Geophys. Res.*, 24, 3257-3260, 1997.
- Vinje, T., Fram Strait ice fluxes and atmospheric circulation 1959-2000, *J. Climate*, 14, 3508-3517, 2001.

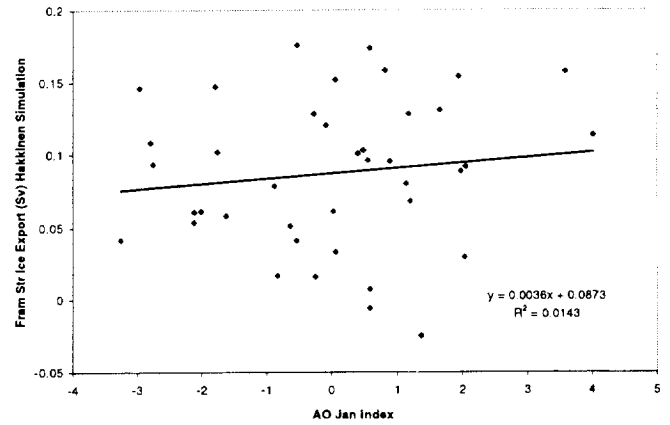
**Figures**

1. Time series of simulated January Fram Strait ice export from both the Häkkinen and Hilmer models with January NAO index (top), January AO index (middle), and January wave 1 phase (bottom) for the period 1958-1997.
2. Scatter plots of the January Fram Strait ice export from the Häkkinen model for the years 1958-1997 versus (A) NAO January index, (B) AO January index, (C) wave 1 phase, and (D) wave 1 phase minus data for 1966 and 1967. Linear least squares fit and variance explained is shown for each plot.
3. Scatter plots similar to those shown in Figure 2, but for the periods 1958-1979 and 1980-1997. The plots involving wave 1 phase data do not include data for 1966 and 1967.
4. Mean January SLP maps for the years (a) 1958 through 1979, (b) 1980-1997, (c) when wave 1 phase is greater than the mean plus 1 SD, and (d) when wave 1 phase is less than the mean minus 1 SD. The 1000 mb and 1020 mb isolines are in bold.

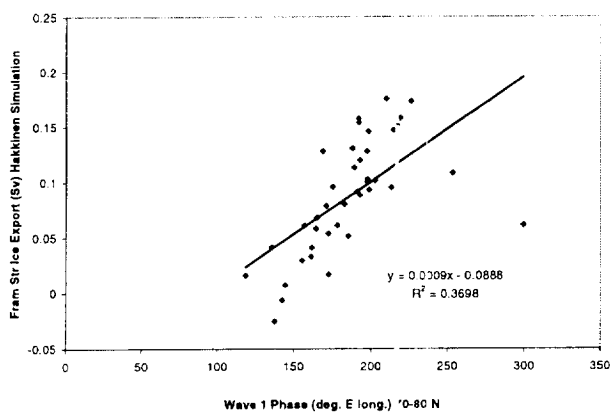




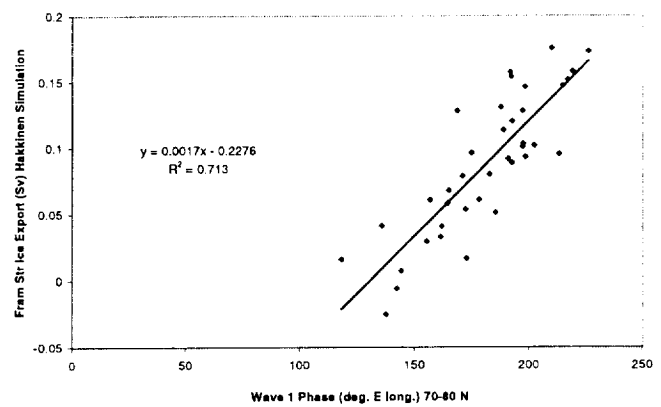
(A)



(B)



(C)



(D)

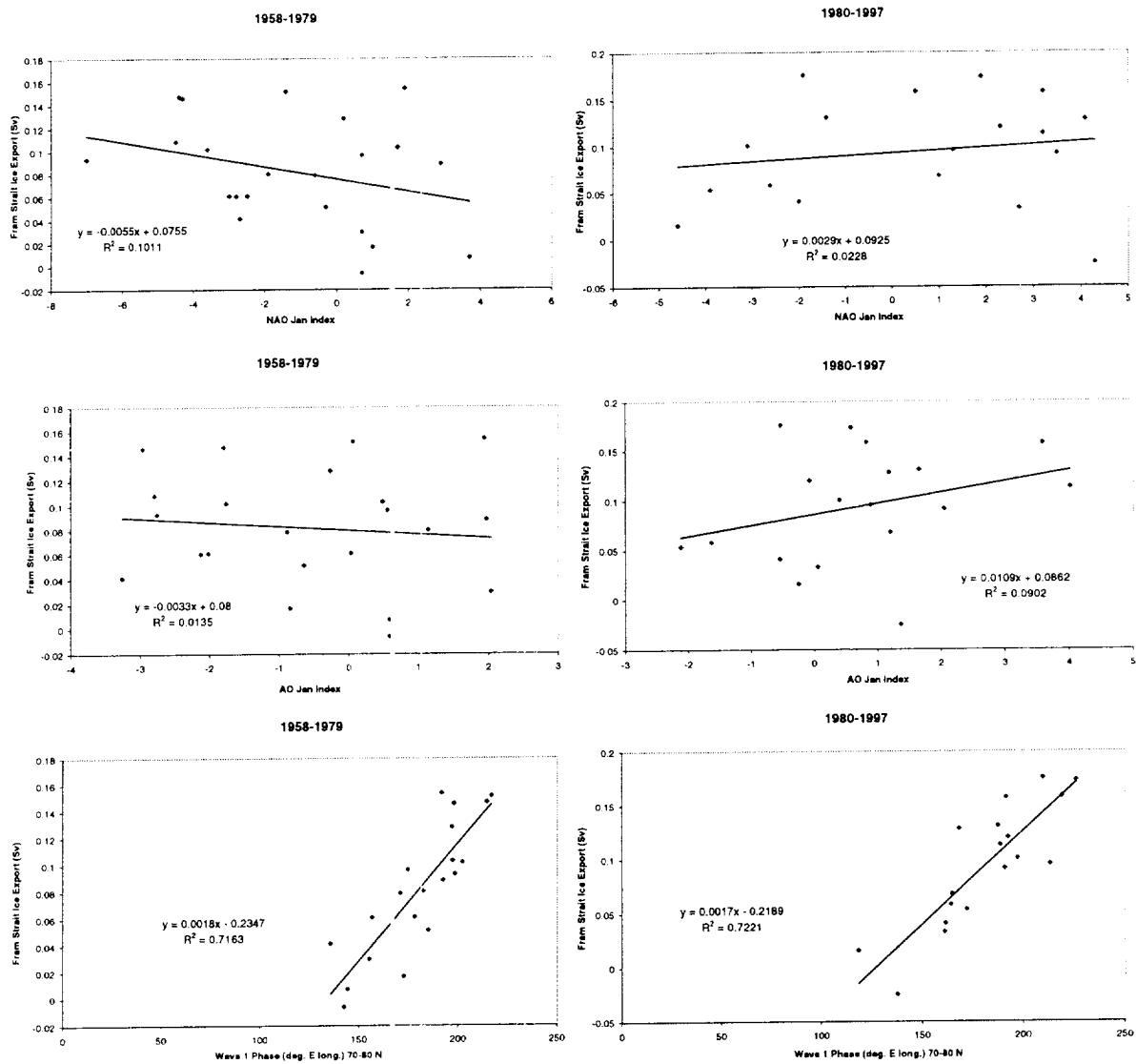


FIG 3

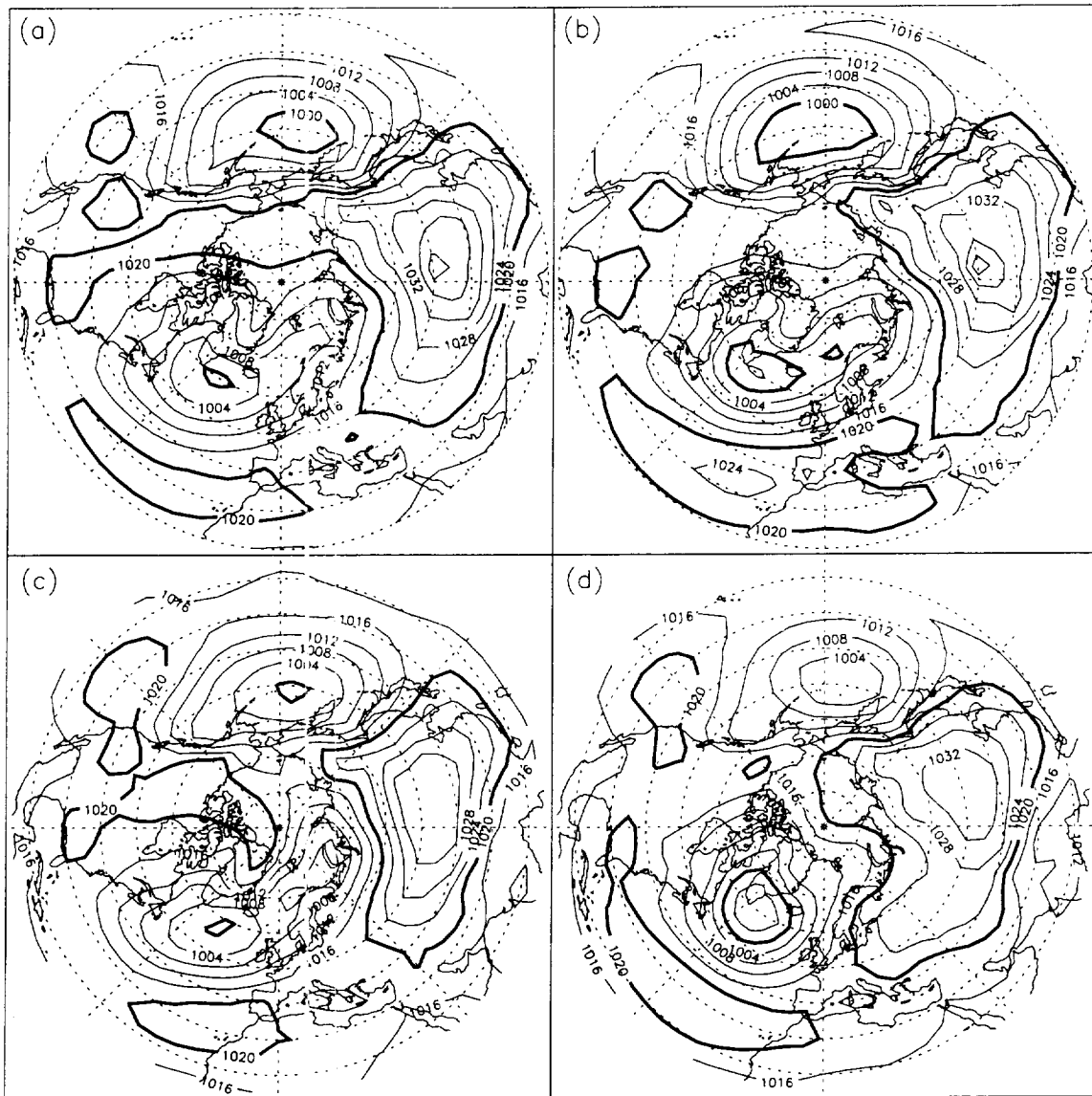


FIG 4